Ain Shams Engineering Journal (2013) **4**, 863–867

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
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MECHANICAL ENGINEERING

Effect of location and dimensions of welded cover plate on stress intensity factors of cracked plates

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Received 17 May 2012; revised 31 December 2012; accepted 16 March 2013
Available online 6 May 2013

KEYWORDS

Welded cover plate;
Stress intensity factor;
Three dimensional finite element

Abstract Three dimensional finite element model was utilized to determine mode I stress intensity factor through the front of a single edge crack in main plate with welded cover plate. The numerical results showed that the ratio of the crack length to the position of the welded cover plate end is a crucial parameter for describing the efficiency of the cover plate location. When the crack tip just reached the cover plate end, the cover plate efficiency is only dependent on the cover plate dimensions regardless the location of the cover plate or the crack length. In the case of crack front not reached the cover plate end, the location of cover plate near the edge of the main plate, i.e., near the crack mouth, is less efficient than that faraway. However, the opposite trend was found for cracks pass beneath the cover plate.

1. Introduction

The transverse cracks in steel plates can propagate under longitudinal axial tension and the resulting ultimate strength reduction due to cracks as indicated by Paik et al. [1]. The longitudinal-edge cracks more significantly reduce the plate ultimate strength [2]. Several methods are considered to reduce the effective stresses around the crack front, e.g., reduction of stress concentration, reinforcement of cracked parts, application of residual compressive stresses, etc. By using auxiliary attachment arresters to the cracked plate either in-plane such as by inserting internal strips or out-of-plane such as bolted, bonded or welded strips can be achieved to fail safe [3–10]. The concept of fail-safe design is used in structures made from either ductile [11] or brittle [12] materials. Integral structures bring the benefits of reduction in part counts, weight saving, and simplification in inspection. However, unlike structures fabricated by mechanical fastening techniques, integral structures do not contain redundant structural members that could act as crack stoppers or retarders; they hence lack fail-safety capability, and regulators penalize such structures by imposing extra design safety factors. In order to improve damage tolerance capabilities, it is important to include fail-safe design features for single load path constructions [11]. The crack

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Peer review under responsibility of Ain Shams University.

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http://dx.doi.org/10.1016/j.asej.2013.03.002

growth in bolted stiffened panel was predicted with the calculated stress intensity factor, SIF [13]. It has been concluded that SIF drops as the crack approaches the stiffener and the reduction becomes larger and it is a maximum when the crack has just passed the stiffener center line. Leme and Aliabadi [14] show that the stiffeners are effective in reducing the stress intensity factors and highly effective in slowing the crack growth rate. Yuen et al. [15] studied the propagation of fatigue cracks in the welded stiffened 350WT steel plates under constant amplitude cyclic loading. Fatigue testing pointed out that the fatigue crack growth rates in stiffened plates were in general lower than that of a corresponding un-stiffened plate. Furthermore, James et al. [16] studied the influence of welded quality and stress relief on the efficiency of welded cover plate for increasing the fatigue life of 6261 Al. alloy I-beam under constant and variable amplitude loading.

Most analytical and numerical investigations were focused on two-dimensional or axisymmetric problems though three-dimensional effects were often acknowledged. In two-dimensional structural analyses, plane strain is commonly assumed where deformation is highly constrained, and plane stress is used for thin plates. However, the state of deformation near the crack tip is always three-dimensional, and the meaning of the two-dimensional LEFM is still not fully understood. Simplicity is the main reason for the popularity of the two-dimensional approach to fracture. In recent years, the development of computers in both speed and capacity has provided better accuracy of solutions in three-dimensional problems involving singularities. The difficulties in obtaining a closed form analysis, three-dimensional analyses using numerical methods were performed by several researchers [17,18].

The main objective of the present work is to study the influence of welded cover plate location and dimensions on mode I stress intensity factor of a through thickness crack in main plates using 3D FEM.

2. Numerical finite element model

The general purpose finite element program ABAQUS was used [19]. A three-dimensional finite element model has been developed to account for geometric and material behavior of isotropic main plate and cover plate. In the present work, the domain integral method commonly used to extract stress intensity factors (SIFs) [20–23].

In a finite element model, SIF can be thought of as the virtual motion of a block of material surrounding each node along the crack line. Each such block is defined by contours: each contour is a ring of elements completely surrounding the nodes along the crack line from one crack face to the opposite crack face. These rings of elements are defined recursively to surround all previous contours. Abaqus/Standard automatically finds the elements that form each ring from the regions given as the crack-line definition. Each contour provides an evaluation of the contour integral. Using the divergence theorem, the contour integral can be expanded into a volume integral, over a finite domain surrounding the crack. This domain integral method is used to evaluate contour integrals in Abaqus/Standard. The method is quite robust in the sense that accurate contour integral estimates are usually obtained even with quite coarse meshes; because the integral is taken over a domain of elements surrounding the crack, errors in local

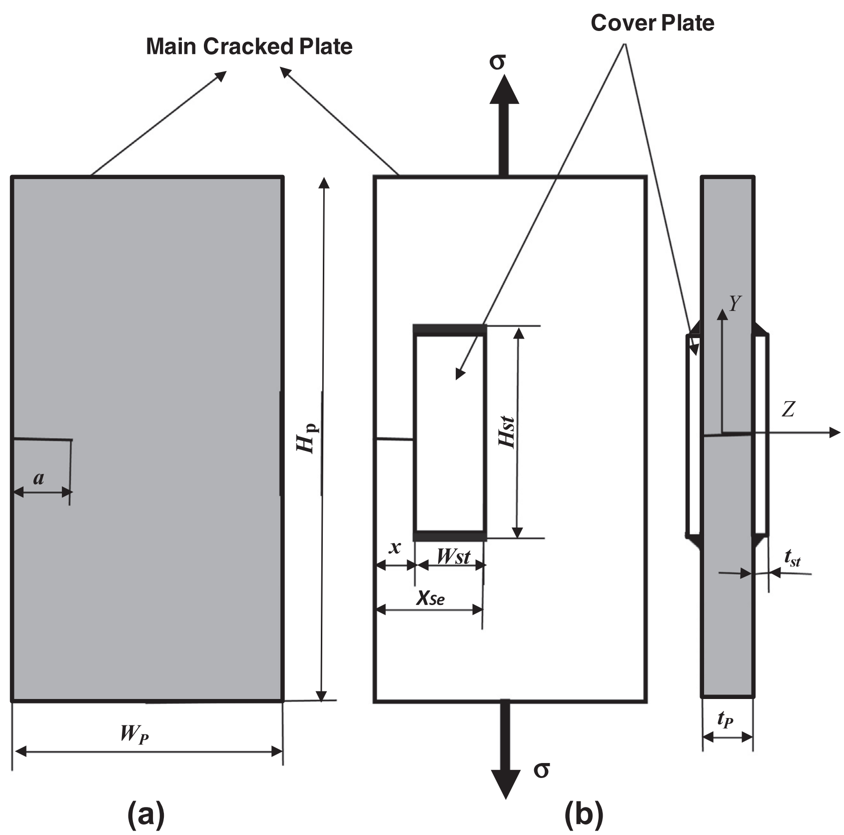

Figure 1 Specimen details – (a) main cracked plate without cover plate (b) main cracked plate with cover plate.

solution parameters have less effect on the evaluated quantities such as the stress intensity factors.

The stress intensity factors K_I, K_{II}, and K_{III} (mode I, mode II, and mode III SIF) are usually used in linear elastic fracture mechanics to characterize the local crack-tip/crack-line stress and displacement fields. They are related to the energy release rate (the J-integral) through

$$J = \frac{1}{8\pi} K^T B^{-1} K \tag{1}$$

where $K = [K_I, K_{II}, K_{III}]^{\mathrm{T}}$ and B is called the pre-logarithmic energy factor matrix [20–23] for homogeneous, isotropic materials B is diagonal and the above equation simplified to

$$J = \frac{1}{\overline{E}}(K_I^2 + K_{II}^2) + \frac{1}{2G}K_{III}^2 \tag{2}$$

where $\overline{E} = E$ (E is modulus of elasticity) for plane stress and $\overline{E} = \frac{E}{(1-v^2)}$ (v is Poisson's ratio) for plane strain, axisymmetry, and three dimension. The energy release rate is calculated directly in Abaqus/Standard.

3. Geometrical definition and material properties

The height of the main plate, H_p, was 150 mm, the width, W_p was 50 mm, and had a thickness, t_p, 5, 10 and 15 mm. The cover plate width, W_{st}, was 12 mm and had a height, H_{st}, 25, 50 and 75 mm, as illustrated in Fig. 1. The ratio of the thickness of both cover plates, $2t_{st}$, to the main plate thickness, $2t_{st}/t_p$, was equal to 0, 0.25, 0.5, and 1. The position of the cover plate, x, equals 0 and 6 mm. The crack length, a, ranged from 3 to 30 mm, $a/w = 0.06$ to 0.6. The finite element meshes constructed with hexagonal structural mesh, C3D8 (8-node linear brick) elements. The mechanical properties of the main plate and cover plate were as follows: modulus of elasticity, $E = 206$ GPa, and Poisson's ratio, $v = 0.3$. The main plate was loaded with uniform uniaxial stress, $\sigma_y = \sigma$, of 100 MPa as shown in Fig. 1. Each cover plate was attached to the main plate by fillet weld at the top and the bottom of the cover plate with thickness equals the cover plate thickness as shown in Fig. 1. The mode I stress intensity factor, SIF, for cracked main plate without cover plate denoted by Y_{Ip} and for cracked plate with cover plate denoted by Y_{Ist}. Y_{Ip} and Y_{Ist} are computed through the crack front from the mid plate thickness where $z = 0$ to free plate surface where $z = t_p/2$.

4. Results and discussion

The effect of cover plate on SIF is presented in Fig. 2 for different cover plate thickness, t_{st}, and different cover plate location, x. It can be seen that, the normalized SIF of cracked plate with cover plate, Y_{Ist} by SIF of cracked plate without cover plate, Y_{Ip}, Y_{Ist}/Y_{Ip}, decreased by increasing the crack length. This is in agreement with the previous work [3,13]. Y_{Ist}/Y_{Ip} decreased by increasing the cover plate thickness. When the crack length reached the cover plate end, $a/(x + W_{st}) = 1$ or $(a/X_{Se}) = 1$ where $X_{Se} = x + W_{st}$, the value of Y_{Ist}/Y_{Ip} is

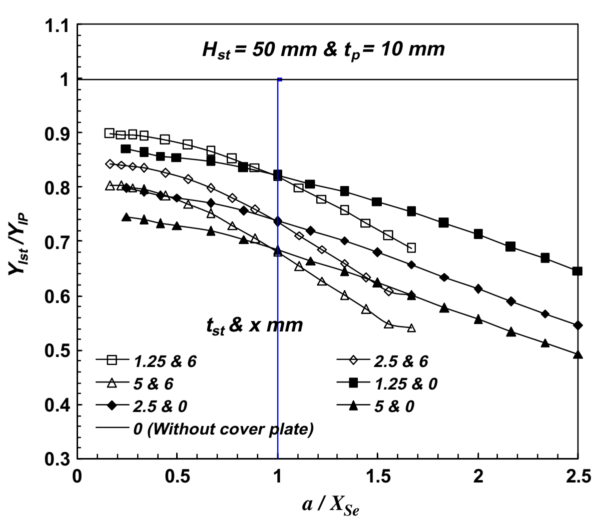

Figure 2 The effect of cover plate location on the normalized mode I stress intensity factor of crack in main plates with different crack length.

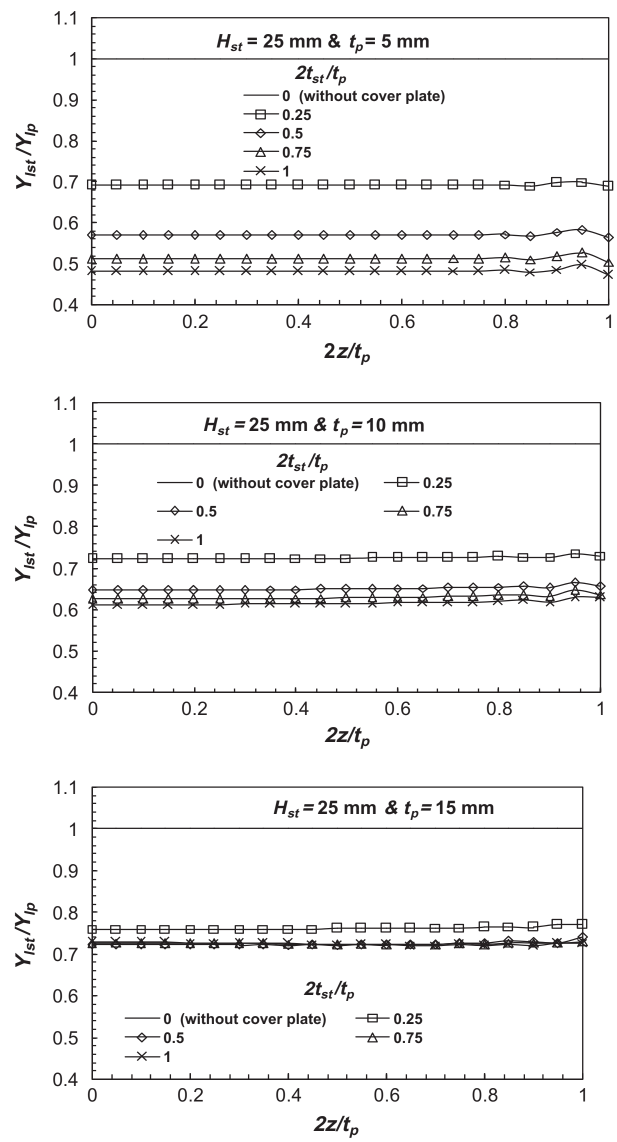

Figure 3 The effect of cover plate thickness on the distribution of the normalized mode I stress intensity factor along crack front for H_{st}, a and x were 25, 12.5 and 0 mm, respectively.

identical for the same cover plate thickness regardless the cover plate location and crack length.

The variation of the normalized Y_{Ist}/Y_{Ip} vs. a/X_{Se} can be divided into two regions. In the first region, the crack did not reach the end of cover plate ($a/X_{Se} < 1$). In this region, the Y_{Ist}/Y_{Ip} increased with increasing "x" for the same cover plate dimensions. In the second region, the crack passed from the cover plate end ($a/X_{Se} > 1$), the Y_{Ist}/Y_{Ip} increased with decreasing "x" for the same cover plate dimensions. In the case of bolted stiffeners, Abdel-Salam et al. [24] used a two dimension finite element model to study the effect of bolted stiffeners location on the SIFs at tip of a crack in strengthened panel. They found that the efficiency of the bolted stiffeners in the reduction of the SIF depends on its location with respect to the crack tip.

Figs. 3–5 show the thickness effect of main plate and cover plate on the normalized mode I SIF, Y_{Ist}/Y_{Ip}, through the crack front of the main plate with constant crack length and cover plate location, i.e., $a = 12.5$ mm and $x = 0$, for different cover plate height, i.e., $H_{st} = 25$, 50, and 75 mm, respectively. Through the crack front, the value of Y_{Ist}/Y_{Ip} was constant from the mid plane (when $2z/t_p = 0$) to $2z/t_p \approx 0.8$ after that Y_{Ist}/Y_{Ip} increased to reach a peak values then should drop to zero at the plate free surface due to the weaker singularity than square root [25], but this is difficult to obtain by the finite element [17] or boundary element [26] analysis. For constant main plate thickness (t_p = constant), Y_{Ist}/Y_{Ip} decreased by increasing the cover plate thickness and decreasing its height. For the same cover plate thickness ratio ($2t_{st}/t_p$), Y_{Ist}/Y_{Ip} increased by increasing the main plate thickness that was agreement with [18]. For a certain main plate thickness, there is a minimum value of Y_{Ist}/Y_{Ip} beyond which there is no effect for increasing cover plate thickness. This value mainly depends on the thickness of the main plate and the length of the cover plate.

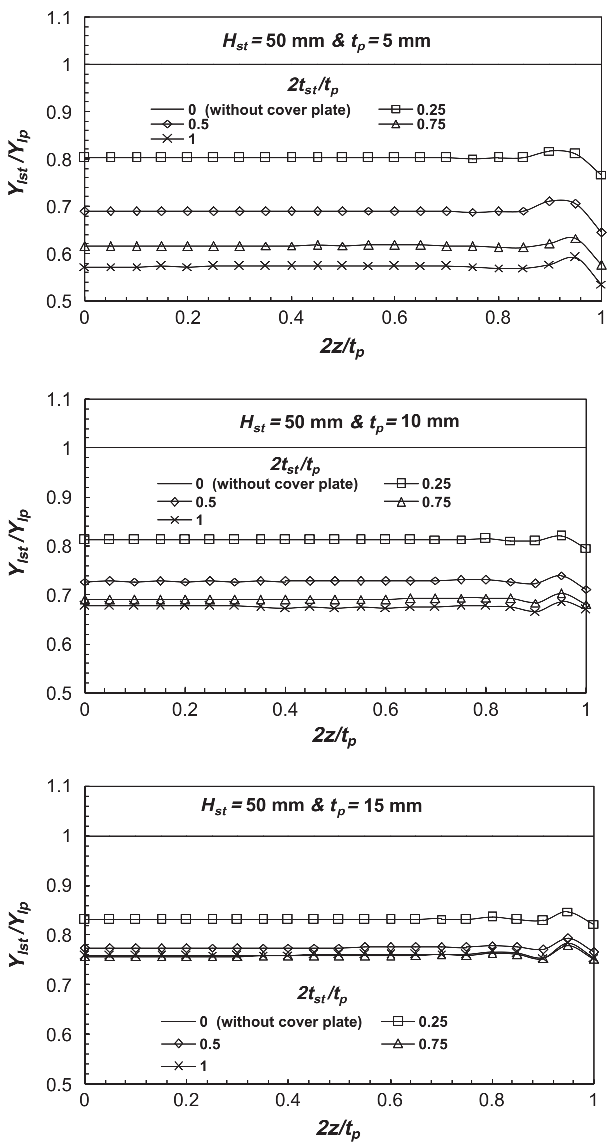

Figure 4 The effect of cover plate thickness on the distribution of the normalized mode I stress intensity factor along crack front for H_{st}, a and x were 50, 12.5 and 0 mm, respectively.

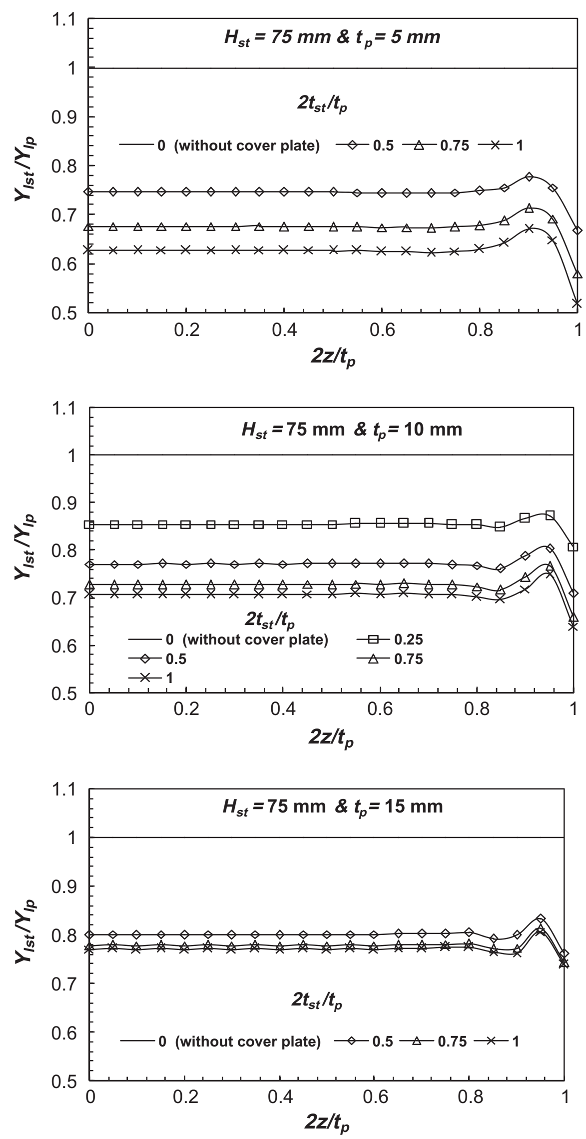

Figure 5 The effect of cover plate thickness on the distribution of the normalized mode I stress intensity factor along crack front for H_{st}, a and x were 75, 12.5 and 0 mm, respectively.

5. Conclusions

It can be concluded from the present work that the normalized SIF Y_{Ist}/Y_{Ip} decreased by increasing the crack length. When the crack length reached the cover plate end, $a/X_{Se} = 1$, the value of Y_{Ist}/Y_{Ip} is identical for the same cover plate thickness regardless the cover plate location and crack length. For $a/X_{Se} < 1$, the cover plate near the edge of the plate is less efficient than that faraway. However, the opposite trend was found for $a/X_{Se} > 1$. The efficiency of a welded cover plate increased by decreasing its height and increasing its thickness. For a certain main plate thickness, there is a maximum efficiency of a welded cover plate beyond which there is no effect for increasing cover plate thickness. This value mainly depends on the thickness of the main plate and the length of the cover plate.

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